Determination of Requirements for Automatic Dependent Surveillance – Broadcast (ADS-B) to ADS-B Three Nautical Miles (nm) Separation Standard

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March 18, 2004

Background

- **FAA currently uses a 3 nmi separation standard in the terminal area with terminal radar**

- **FAA objective is to establish an analytic basis for operational approval of ADS-B as an additional surveillance source that can also support 3 nmi separation in the terminal area**

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Approach for Evaluating Requirements for ADS-B Support of 3 nm Separation Standard

- **Identify Safety Assessment methodology (ICAO)**
  - **Comparison with Reference SSR System Recommended for Evaluation of ADS-B**
  - **Method to assess "close approach" risk (CAP model)**
  - **Use ICAO accepted close approach risk allocated to surveillance**
- **Quantify performance of SSR system to establish reference baseline**
- **Establish threshold ADS-B position accuracy/integrity performance required for equivalent close approach risk to baseline SSR case**
  - **Minimum value of NIC parameter reported in ADS-B that can be accepted for service**

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ICAO Doc 9689-AN/953 Identifies Two Safety Assessment Alternatives

- **Comparison of proposed system risk with a reference system risk**
  - Compares proposed system with a system that has already been judged to be acceptably safe
  - Reference system must be considered sufficiently similar to proposed system for comparison
- **Evaluation of proposed system risk against a threshold**
  - Absolute method where explicit relation between system characteristics and collision risk is compared against a maximum tolerable risk
  - Required when a radical change is planned that has not previously been tried in other regions

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Comparison with Reference Secondary Surveillance Radar (SSR) System Recommended for Evaluation of ADS-B

- **ICAO requirements for similarity of reference and proposed systems**
    - **Separation minima must not be less in proposed system**
    - **Proposed communication and surveillance must not be worse in terms of accuracy, reliability, integrity, and availability**
    - **Frequency and duration of the application of minimum separation between aircraft must not be greater in proposed system**
    - **Navigation performance of aircraft population should be no worse in its effect on collision risk in any dimension in the proposed system**
- **All factors except surveillance are assumed to be unchanged in the proposed 3 nm separation standard based on ADS-B surveillance.**

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Recommended Reference System Baseline Criterion for 3 nm Separation Standard

- **Reference system baseline is specified by the ATC operational standard (FAA 7110.65N sec 5-5-4) for a minimum separation of 3-nm for co-altitude aircraft within 40 nm of a single sliding window SSR**

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Attributes of Reference SSR Baseline

- Baseline performance for reference SSR system relates to the position uncertainty in ATC displayed radar plot data (with a 5 sec scan-to-scan update interval in terminal areas)

- For a worst case example at long range, cross-range errors due to azimuth measurement are greater than along-range measurement errors

- Cross-range error std dev, $\sigma_y = R\,\sigma_\varphi$, where σ_φ is the Az angle error std dev (in radians) and R is range to target (in nm)

- Based on available data for sliding window SSRs, $\sigma_\varphi = 0.23$ deg (4 mrad) with a Gaussian error distribution (eyeball fit of U.S. data)

- Position estimates are essentially simultaneous for adjacent aircraft at same range, and the relative cross-range separation measurement, $y = R\,(\varphi_2 - \varphi_1)$, is unbiased

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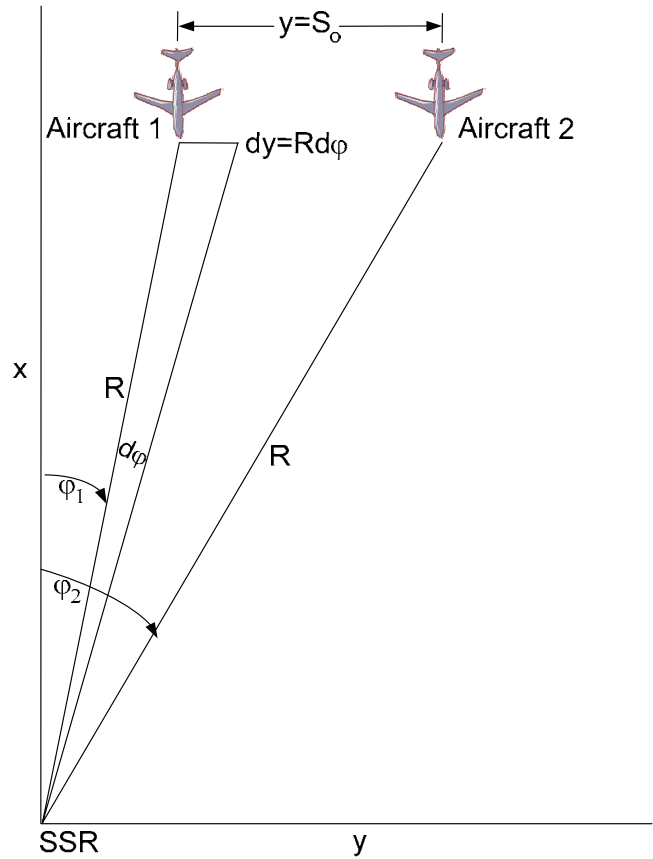
ICAO CAP Model Overview for Assessment of Radar Separation Risk

- **CAP is the probability, Pca, the adjacent aircraft pair of width, Aw, actually overlap when the apparent separation is the separation minimum, So. For a cross-range separation, y,**

  Pca = Prob[y < Aw|So].

- **With some math, Pca is given by**

$$Pca = 2Aw\int_{-\infty}^{\infty} p1(y)\,p1(y - So)\,dy$$

  - **Where p1(y) is the pdf for aircraft 1 position error at y = 0, and p2(y) = p1(y-So) is the pdf for aircraft 2 position error when apparently separated by y = So**

  - **Errors are independently distributed with zero mean**

- **Determine So for values of Pca no greater than <u>ICAO accepted which are on the order of 10^{-12}</u>**

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Geometry for SSR Reference System Risk Assessment

Diagram labels:
- $y=S_o$
- Aircraft 1
- $dy=Rd\varphi$
- Aircraft 2
- R
- $d\varphi$
- R
- φ_1
- φ_2
- x
- SSR
- y

$Pca = Prob(y<Aw|S_o)$

S_o = Apparent Separation
Aw = Aircraft Width
R = 40 nm
$\sigma\varphi$ = 0.23 degrees
$p1(y)$ = position error pdf for aircraft 1 at y = 0
$p1(y-S_o)$ = position error pdf for aircraft 2 at y = So

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Gaussian Probability Density Functions, p1 and p2, for SSR CAP Calculations when So = 1 nm

$$\sigma y := 40 \cdot 4 \cdot 10^{-3} \qquad \sigma y = 0.16 \qquad Aw := 0.033 \qquad So := 1$$

$$p1(y) := \frac{1}{\sqrt{2 \cdot \pi \cdot \sigma y^2}} \cdot \exp\left(\frac{-y^2}{2 \cdot \sigma y^2}\right) \qquad p2(y) := p1(y - So) \qquad y := -0.5, -0.49 .. 1.5$$

Cross-range error pdfs for adj aircraft

AC 1 pdf
AC 2 pdf

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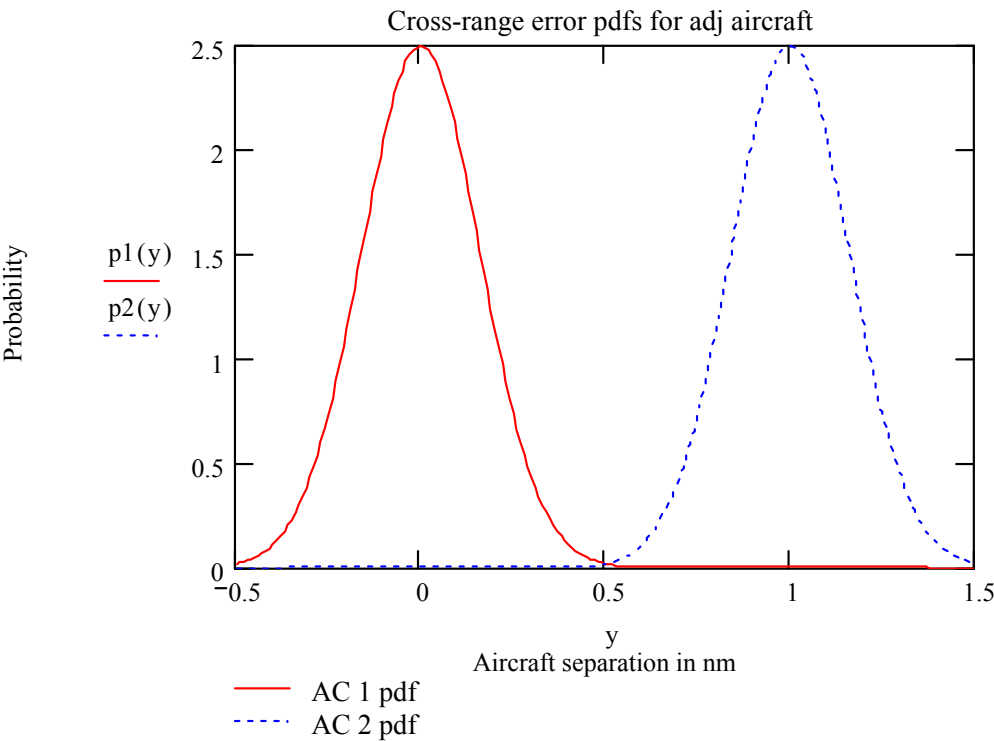
Sensitivity of CAP Results with So for Assumed Gaussian Error pdf in Reference SSR System

$\sigma y = 0.16 \qquad Aw := 0.033$

$$Pca(So) := 2 \cdot Aw \cdot \int_{-\infty}^{\infty} p1(y) \cdot p1(y - So) \, dy$$

$So := 1 \qquad Pca(So) = 6.678 \times 10^{-6}$

$So := 1.6 \qquad Pca(So) = 1.616 \times 10^{-12}$

$So := 1.7 \qquad Pca(So) = 6.44 \times 10^{-14}$

- **Reference system separation standard is 3 nm cross-range separation 40 nm from single sliding window SSR**
- **Reference baseline CAP risk level is Pca = 6.4 x 10^{-14} at a separation So = 1.7 nm for this pdf**
- **Difference in So and 3 nm standard is a <u>margin of 1.3</u> nm for other factors that may affect minimum separation**
- **<u>This margin should be preserved with ADS-B surveillance for equivalent safety</u>**

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ADS-B to ADS-B Separation Risk Assessment

- **Comparison of Proposed ADS-B System with Reference SSR System**
- **Features of Proposed ADS-B System**
- **GPS/ADS-B Horizontal Position Data and Integrity Monitor Characteristics**
- **RAIM Concept Illustrated for Assumed 1-DOF Chi Sq Distribution (five satellites in view)**
- **CAP Evaluation Approach for Proposed ADS-B to ADS-B Risk Assessment**
- **CAP Model for ADS-B to ADS-B Minimum Separation Evaluation**
- **Evaluation Summary for ADS-B to ADS-B 3-nm Separation Standard**
- **ADS-B Reception Requirements to Meet the Reference System SSR Update Rate**

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Comparison of Proposed ADS-B System with Reference SSR System

- **A maximum ADS-B separation minimum of 1.7 nm is required to preserve the same operation margin of 1.3 nm available today with 3-nm SSR separation standard (Conservative criterion)**
- **Surveillance Update:**
  - **SSR update estimates on adjacent aircraft are made at essentially the same time (in time registration);**
  - **ADS-B report updates on adjacent aircraft are asynchronous**
- **Integrity:**
  - **SSR integrity, although not quantified, is high and assured by monitoring parrots and staff.**
  - **ADS-B integrity based on GPS fault detection monitored by Receiver Autonomous Integrity Monitoring (RAIM) and Wide Area Augmentation System (WAAS) in service area**

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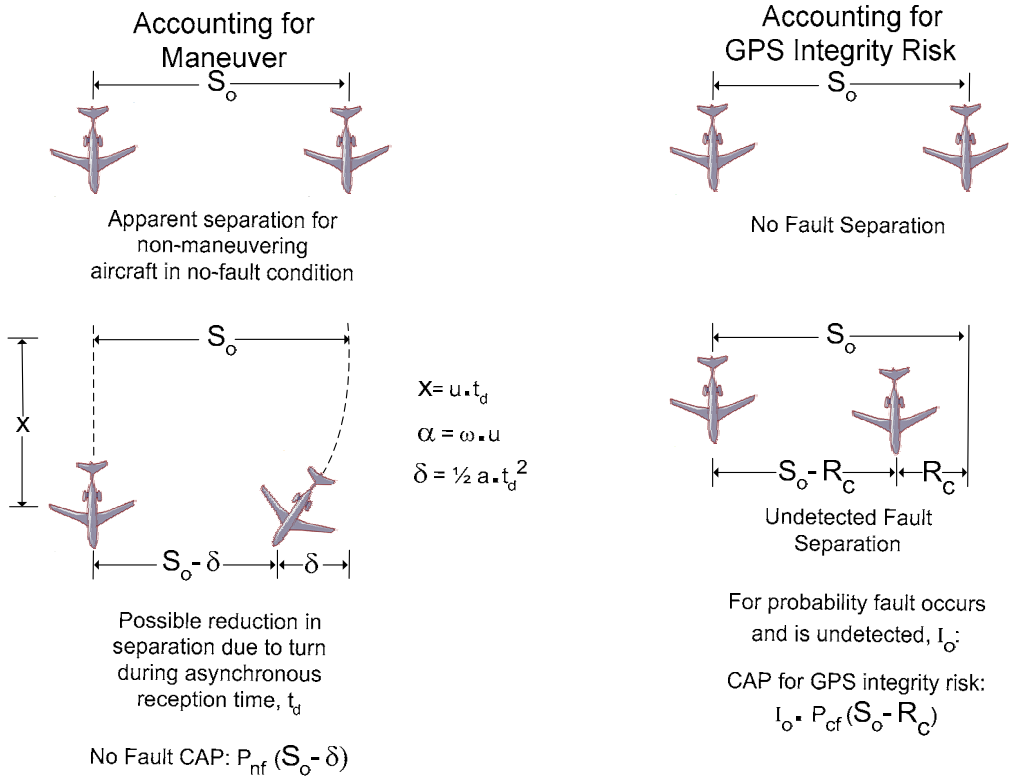
Features of Proposed ADS-B System

- **GPS fault of interest for integrity is an undetected position error associated with use of a failed satellite in the position solution**

- **Onboard GPS source for ADS-B is certified for navigation applications and, at a minimum, has RAIM capability for fault detection**

- **GPS monitoring provides 95% bound on accuracy and a HPL error containment radius, Rc, at an integrity risk level of 10^{-7}/hr (conservative upper bounds for WAAS)**

- **Worst case failure mode is for fault to affect only one aircraft of an adjacent pair in a direction that reduces their separation**

- **Close proximity duration is assumed to be 30 min for conversion of failure rates to operational surveillance risks**

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GPS/ADS-B Horizontal Position Data and Integrity Monitor Characteristics

- **A position error occurs if an undetected satellite fault condition pseudo-range bias error contributes to the position solution. When 5 or more satellites are in view, the GPS HPL output assures this error to be no greater than a containment radius, Rc, at a navigation integrity risk level of 10^{-7}/hr. ADS-B quantizes Rc as a corresponding NIC value at an associated surveillance integrity risk level, SIL = 10^{-7}/hr**

- **Separation is conservatively assumed to be reduced by the NIC value if an undetected fault occurs**

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CAP Evaluation Approach for Proposed ADS-B to ADS-B Risk Assessment

Accounting for Maneuver

S_o

Apparent separation for non-maneuvering aircraft in no-fault condition

S_o

X

$X = u \cdot t_d$

$\alpha = \omega \cdot u$

$\delta = \frac{1}{2} a \cdot t_d^2$

$S_o - \delta$ δ

Possible reduction in separation due to turn during asynchronous reception time, t_d

No Fault CAP: $P_{nf} (S_o - \delta)$

Accounting for GPS Integrity Risk

S_o

No Fault Separation

S_o

$S_o - R_c$ R_c

Undetected Fault Separation

For probability fault occurs and is undetected, I_o:

CAP for GPS integrity risk:
$I_o \cdot P_{cf} (S_o - R_c)$

Total CAP, $P_{ct} = P_{nf} (S_o - \delta) + I_o \cdot P_{cf} (S_o - R_c) - O(0)$

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CAP Model for ADS-B to ADS-B Minimum Separation Evaluation

ADS-B separation:

$$\sigma g := \frac{92.6}{1852} \qquad \sigma g = 0.05 \qquad Aw := 0.033$$

Close Approach Probability Model:
So = apparent separation
σ = std dev of horizontal position
Aw = aircraft dimention
p(y) = Gaussian pdf
Rc = horizontal containment radius

$$B := 8.3 \qquad sm := 1.5 \qquad Rcg := B \cdot sm \cdot \sigma g \qquad Rcg = 0.623$$

$$pm := 10^{-3} \qquad te := 30$$

$$Io := \frac{te}{60} pm \cdot 10^{-4} \qquad Io = 5 \times 10^{-8}$$

$$\sigma g = 0.05 \qquad Rc := 1.0 \qquad \text{NIC Rc =/>Rcg}$$

$$pg(y) := \frac{1}{\sqrt{2 \cdot \pi \cdot \sigma g^2}} \cdot \exp\left(\frac{-y^2}{2 \cdot \sigma g^2}\right) \qquad So := 1.4 \qquad SE := So + 3 \cdot \sigma g \qquad y := -0.2, -0.199 .. SE$$

Loss of separation with parallel aircraft off-set by So durning ADS-B report registration delay, td sec, when accelaration errors associated with ω for time, td, are uncompensated:

ADS-B a/c velocity (u in kts) and turn rate (ωd in deg/sec): $\quad u := 540 \qquad \omega d := 6 \qquad td := 5$

ADS-B a/c acceleration: $\qquad \omega := \omega d \cdot \dfrac{\pi}{180} \qquad \omega = 0.105 \qquad a := \omega \cdot u \cdot 1.7 \qquad a = 96.133$

$$\delta := \frac{1}{2} \cdot \frac{a \cdot (td)^2}{6000} \qquad \delta = 0.2 \qquad \gamma t := \omega d \cdot (td) \qquad \gamma t = 30$$

Pca for no fault but possible turn

$$Snf := So - \delta \qquad Pnf(Snf) := 2 \cdot Aw \cdot \int_{-\infty}^{\infty} pg(y) \cdot pg(y - Snf)\, dy \qquad Pnf(Snf) = 0$$

Pca for GPS fault integrity risk

$$Sa := So - Rc \qquad Pcf(Sa) := 2 \cdot Aw \cdot \int_{-\infty}^{\infty} pg(y) \cdot pg(y - Sa)\, dy \qquad Pcf(Sa) \cdot Io = 2.047 \times 10^{-15}$$

Total CAP: $\quad Pct(Sa, Snf) := Pnf(Snf) + Io \cdot Pcf(Sa) \qquad Pct(Sa, Snf) = 2.047 \times 10^{-15}$

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Evaluation Summary for ADS-B to ADS-B 3-nm Separation Standard

- Assessment assumes undetected GPS error reduces separation, and includes margin if one aircraft turns toward the other during the asynchronous reception interval

- Reference SSR system evaluation criterion of So = 1.7 nm is conservatively based on optimistic assessment of SSR error distribution

- ADS-B comparative value of So = 1.4 nm at similar Pca risk level is obtained for σ = 92.6 m and Rc = 1.0 nm (NIC = 5) at a SIL = 10^{-7}/hr.

- NIC/NAC values this good or better support an ADS-B to ADS-B 3 nm separation standard with a risk no greater than that currently accepted with radar separation. Note: NIC = 5 with SA ON, and NIC = 6-8 with SA off

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ADS-B Reception Requirements to Meet the Reference System SSR Update Rate

- **ATC automation system requires reference SSR system updates at a 5 sec interval with 95% blip/scan reliability**

- **Equivalent capability for UAT with a 1/sec state vector broadcast rate means**
  - **Po = 1 – q^5 where Po = 0.95 and q = single message prob failure**
  - **From this, q = 0.55, or p = 0.45 is the minimum acceptable single message prob of reception to meet reference system update rate**

- **Maximum coverage for 3 nm separation UAT service volume is defined by a probability of reception at least 0.45**

- **Similar examination of 1090 ES report assembly requirements define coverage for this link alternative**

- **Notice SSR cross-range accuracy degrades with range from SSR, whereas ADS-B update rate degrades with range from GBT**

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Summary and Conclusions

- Risk assessment for 3 nm minimum separation with ADS-B/GPS follows ICAO recommended comparative evaluation with similar reference system (SRS)

- Comparative surveillance risks determined by extension of ICAO approved CAP model and available SSR and GPS data

- Worst case assumptions assure conservative assessment

- Resulting NIC = 5 requirements for ADS-B to ADS-B, and are lenient enough to assure high GPS availability. Even GPS with SA ON (NACp = 8 and NIC = 5) meets these requirements

- Need to address case of ADS-B to SSR

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References

- [1] 1998, "Manual on Airspace Planning Methodology for the Determination of Separation Minima," ICAO Doc 9689-AN/953, 63-65.
- [2] Fall 2003, Jones, S. R., "ADS-B Surveillance Quality Indicators: Their Relationship to System Operational Capability and Aircraft Separation Standards" ATC Quarterly.
- [3] RPN MASPS, RTCA DO-236A section B.2.2.
- [4] Bradford, Steve, unpublished FAA report.
- [5] MOPS for GPS/WAAS Equipment, RTCA DO-229C Appendix J.
- [6] 2001, Van Dyke, K.L., "GPS Availability and Outage Reporting for Aviation Applications," Air Traffic Control Quarterly, Vol. 9(3), 175-210.
- [7] 1996, Lee, Y.C., Van Dyke, K.L., DeCleen, B., Studenny, J., Beckmann, M., "Summary of RTCA SC-159 GPS Integrity Working Group Activities," Proceedings of the 1996 National Technical Meeting of the Institute of Navigation, Santa Monica, CA.
- [8] 1998, Brown, R.G., and Chin, G.Y., "GPS RAIM: Calculation of Threshold and Protection Radius Using Chi-Square Methods – A Geometric Approach," Institute of Navigation, GPS Red Book Series, Volume V.

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Anti-spoofing of ADS-B targets

- **Malicious broadcast of false ADS-B targets could present a nuisance to users**

- **Acceptance of false targets can be minimized with the independent range measurement available with UAT**

- **Acceptance of false targets can be minimized with 1090 ES by use of multi-sector antennas on aircraft, or with multi-sector antennas or multilateration on the ground**

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Error pdfs for ADS-B to ADS-B Separation Standard Evaluation

$\sigma g = 0.05$ $Rc = 1$ $Io = 5 \times 10^{-8}$ $Sa = 0.4$ $\delta = 0.2$ $Aw = 0.033$

$Pct(Sa, Snf) = 2.047 \times 10^{-15}$ $So = 1.4$ $\dfrac{So}{\sigma g} = 28$ $\dfrac{Snf}{\sigma g} = 23.994$ $\dfrac{Sa}{\sigma g} = 8$

pg(y), pg(y−Sa), pg(y−Snf), pg(y−So)

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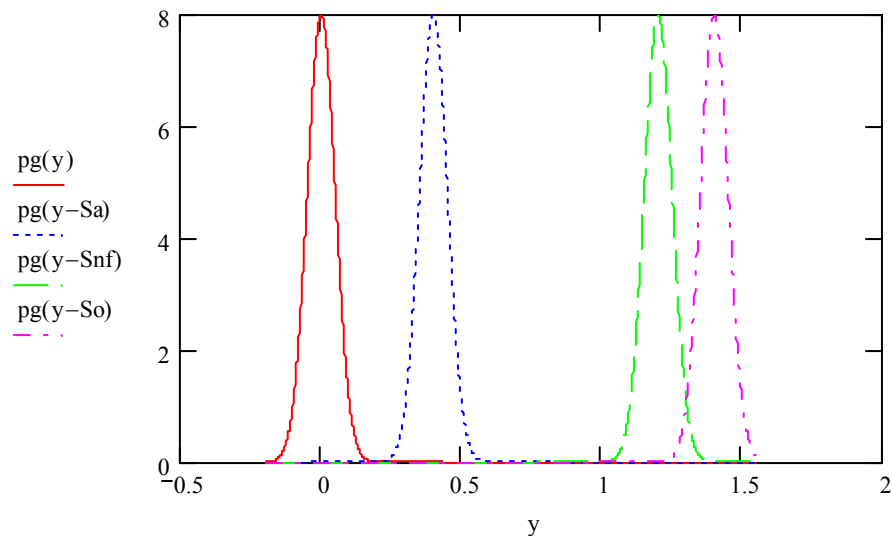
Risk Evaluation Sensitivity for Alternate Reference SSR System Error Distribution

- **Since detailed wide angle error distribution data is unavailable for SSRs operating in typical NAS environments, examine baseline sensitivity to two assumed distributions:**
  - **Gaussian as generally indicated by available NAS data**
  - **Piecewise Gaussian giving greater weight to wide angle errors**

- **Use the more demanding requirement for comparison unless better data becomes available**

- **Worst case ADS-B is then compared with best case SSR reference at same or lower risk level**

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CAP Model and Results for Piecewise pdf Scaled From Japanese Data Over Ocean

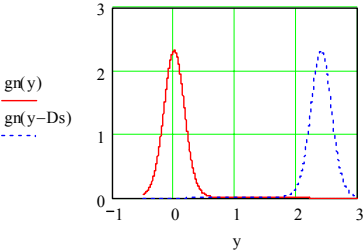Normal-Normal pdf model in NM $Ds := 2.4$ $Rmx := 40$ $\alpha := 0.1640$ $en := 0.23$

$$\sigma1 := en \cdot \frac{\pi}{180} \cdot Rmx \qquad \sigma1 = 0.161 \qquad \sigma2 := 1.66 \cdot en \cdot \frac{\pi}{180} \cdot Rmx \qquad \sigma2 = 0.267 \qquad Aw := 0.033nm$$

$$pn1(\zeta) := \frac{1}{\sqrt{2 \cdot \pi \cdot \sigma1^2}} \cdot \exp\left(\frac{-\zeta^2}{2 \cdot \sigma1^2}\right) \qquad pn2(\zeta) := \frac{1}{\sqrt{2 \cdot \pi \cdot \sigma2^2}} \cdot \exp\left(\frac{-\zeta^2}{2 \cdot \sigma2^2}\right)$$

$$gn(y) := (1 - \alpha) \cdot pn1(y) + \alpha \cdot pn2(y) \qquad y := -0.5, -0.499 .. 3 \qquad u := [(1 - \alpha) \cdot \sigma1 + \alpha \cdot \sigma2] \cdot 2.9$$

$$C(Ds) := \int_{-\infty}^{\infty} gn(y) \cdot gn(y - Ds)\, dy \qquad Pca(Ds) := 2 \cdot Aw \cdot C(Ds) \qquad C(u) := \int_{-u}^{u} gn(\zeta)\, d\zeta$$

$$C(u) = 0.193$$

Sliding window separation model at Rmx in NM

$Ds = 2.4$ $Rmx = 40$

$\sigma1 = 0.161$ $\sigma2 = 0.267$ $\alpha = 0.164$

$Pca(Ds) = 2.964 \times 10^{-12}$

gn(y)
gn(y−Ds)

- **Reference SSR for 3-nm minimum is represented by same accuracy but higher probability of wide angle errors**
- **Reference baseline CAP risk level is Pca = 3.0 x 10^{-12} at a separation Ds = 2.4 nm for this assumed pdf**
- **Difference in this Ds and 3 nm minimum for piecewise Gaussian errors is a margin of 0.6 nm for the other factors that may affect minimum separation in the reference system.**

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Summary of Assumed SSR Reference System Baseline Characteristics

- **Alternate assumptions made on wide angle error distribution for sliding window SSR over typical terrain since detailed SSR error distribution data is unavailable**
  - **Optimistic: Gaussian pdf with $\sigma\varphi$ = 0.23 deg**
  - **Conservative: Scaled piecewise Gaussian pdf (same near in accuracy but more errors at wide angles)**
- **Optimistic model yields more demanding reference system baseline requirement for proposed ADS-B surveillance system risk comparison**
  - **ADS-B must support separation minimum of no greater than 1.7 nm at a Pca = 6.4×10^{-14} surveillance risk level**
  - **Alternate CAP minimum separation of 2.4 nm leaves smaller margin for other operational considerations**
- **Use 1.7 nm at a Pca = 6.4×10^{-14} surveillance risk level as reference baseline thus assuring conservative ADS-B assessment**

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